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1 **Zero Carbon Energy System of South East Europe in 2050**

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ABSTRACT

South East Europe is the region in a part of Europe with approximately 65.5 million inhabitants, making up 8.9 % of Europe's total population. The countries concerned have distinct geographical features, various climates and significant differences in gross domestic product per capita, so the integration of their energy systems is considered to be a challenging task. Large differences between energy mixes, still largely dominated by fossil-fuel consumption, make this task even more demanding.

This paper presents the transition steps to a 100 % renewable energy system which need to be carried out until the year 2050 in order to achieve zero carbon energy society. Novelty of this paper compared to other papers with similar research goals is the assumed sustainable use of biomass in the 100% renewable energy system of the region considered. It is important to emphasize here that only the sustainable use of biomass can be considered carbon-neutral. The resulting biomass consumption of the model was 725.94 PJ for the entire region, which is in line with the biomass

potential of the region. Modelling the zero-carbon energy system was carried out using the smart energy system concept, together with its main integration pillars, i.e. power-to-heat and power-to-gas technologies. The resulting power generation mix shows that a wide variety of energy sources need to be utilized and no single energy source has more than a 30 % share, which also increases the security of supply. Wind turbines and photovoltaics are the main technologies with shares of 28.9 % and 22.5 %, followed by hydro power, concentrated solar power, biomass (mainly used in cogeneration units) and geothermal energy sources. To keep the biomass consumption within the sustainability limits, there is a need for some type of synthetic fuel in the transportation sector. Nevertheless, achieving 100 % renewable energy system also promises to be financially beneficial, as the total calculated annual socio-economic cost of the region is approximately 20 billion euros lower in the year 2050 than in the base year. Finally, energy efficiency measures will play an important role in the transition to the zero-carbon energy society: the model shows that primary energy supply will be 50.9 % lower than in the base year.

Keywords: smart energy system; renewable energy system; zero carbon; South East Europe; sustainable biomass; energy efficiency

1. INTRODUCTION

Countries in the South East Europe (SEE) region have been facing various common problems related to the energy sectors. Energy markets are generally small and energy prices are below economic level, while countries' economies are energy intensive. Furthermore, tariff structures are undeveloped and poor infrastructure as well as history of conflicts complicate energy trade in the region [1]. Therefore, regional cooperation of the SEE countries, integration of energy systems and harmonization of

72 legislations is necessary. In order to increase security of supply, economic efficiency and use of
73 renewable energy sources (RES), which are important for future energy systems, as well as to reduce
74 market concentration, common energy system has to be created [2]. Nevertheless, transition to clean
75 renewable energy systems can be beneficial in economic, energy-environmental and sociological terms
76 [3].

77 With the population of approximately 65.5 million inhabitants, SEE region makes around 8.9 % of
78 Europe's total population [4]. An average median age of the population in the year 2014 was 39.8
79 years, which is about 6 % below the average of the European Union (EU28) [5], while the rate of
80 population older than 60 was 22 %. Urban population accounts for 59 % of the total population in
81 the region: Bulgaria having the highest rate of urban population with 75 %, while the lowest share
82 has Bosnia and Herzegovina (B&H) with 50 %. The region recorded depopulation between years
83 2013 and 2014 at a level of 0.14 %, which is largely due to the fact that the total number of
84 emigrants from SEE countries was 77,342 [4]. Differences in economic development within the
85 region are significant, since the highest gross domestic product (GDP) per capita of 23,962 \$
86 records Slovenia and the lowest GDP of 3,877 \$ has Kosovo, also the Europe's youngest country
87 [6]. Therefore, average GDP per capita of 9,922 \$ is only 28 % of the EU28 average. Great
88 differences can be noticed in geographical characteristics and climate conditions as well. Region
89 consists of several main geographical features, from mountain chains such as the Alps, Dinarides
90 and Carpathians extending through Slovenia, Croatia, B&H, Serbia, Montenegro and Kosovo to the
91 Mediterranean and Ionian Sea in Greece and Adriatic Sea in Croatia, Montenegro and Albania.
92 Total area of the region is 765,884 km², Romania being the largest country by far with 238,391 km²
93 (or 31 % of the total area), while Slovenia and Montenegro are the smallest, with 20,256 km² and
94 13,812 km², respectively. Average population density is 85.5 people/km², which is 23.6 % lower
95 than the EU28 average [6]. Southern part of the region, with a moderate climate and dry summers

96 with a large number of sun hours, distinguishes from northern and eastern part's continental climate,
97 with long and hot summers, but also cold and intensive winters [7].

98

99 State of the art of regionally integrated energy systems, and impacts of the integration on countries
100 involved, is described in the following articles. Authors in [8] analyse the advantages of regionally
101 integrated electricity supply system in comparison with power generation system of individual
102 countries in the Western Africa. Results show that integrated system has 38 % lower total electricity
103 production compared to individual systems. The advantages of inter-regional integration of electricity
104 market for the case of East China have been analysed in [9]. Results demonstrate that electricity
105 utilities in the inter-regional electricity market dispose with larger generation capacity, while market
106 can benefit from more optimal usage of resources and capacity. Challenges of greater regional energy
107 co-operation in the South Asia region, one of the fastest growing regions in the world, have been
108 discussed in [10], while social cost-benefit analysis of two electricity interconnector investments in
109 Europe has been conducted in [11]. In [12] authors show how the cross-border electricity transmission
110 has a significant importance when a country or a region has an increased electricity production from
111 intermittent RES. Furthermore, author in [13] describes the case of Nordic countries, the world leaders
112 in electricity production from RES, which achieved successful regional cooperation which should be
113 followed by other countries and regions. Analysis in [14] shows that the penetration level of RES is
114 highly determined by the flexibility of the system. Finally, in order to reach the goals from [15],
115 storage and balancing synergies have to play an important role in future energy systems.

116 Evaluation of reliability of Integrated Energy System (IES) has been conducted in [16]. Authors
117 analysed IES as a regional energy system that includes various sub-systems, such as electricity, gas,
118 heating and cooling, and other energy supply systems. Importance of integration of electrical and

119 heating systems, in order to facilitate implementation of RES, is also emphasized in [17]. Authors
120 concluded that cooperation between these two sectors can reduce fuel consumption and energy losses.
121 Novelty in this paper is interplay between transport and industry sectors with energy supply systems
122 (heat and electricity), which increases possibility to integrate even more fluctuating RES and reduce
123 fuel consumption and losses further.

124 In [18] author provides an overview of the electricity production systems in 10 countries in SEE
125 during 1995-2004 and investigates the potential of integration of electricity markets. Author
126 concludes that an efficient regional energy market would help to meet peak demand in individual
127 countries and significantly increase reliability and stability of electricity supply across the region.
128 However, it emphasizes high level of dependency on hydro and thermal (fossil and nuclear)
129 electricity production. Congestion management methods, as well as infrastructural transmission
130 assets in the region are described in [19]. This paper also stresses importance of establishing
131 regional electricity market in order to allow more cost-effective electricity production. European
132 Union electricity reform is explained in [20], together with its relation to the SEE electricity market.
133 Paper expresses doubts that EU model is completely applicable and good for SEE region.
134 Furthermore, The Energy Community, experiment in a creation of regional energy market between
135 the EU and SEE partners, is described in [21]. Achievements in the process of establishing a stable
136 market framework and regulation conditions within the Energy Community are described in [22].
137 Here author also emphasizes importance of the SEE regional electricity market formation as a first
138 step towards the integration with the EU market. Within the 2030 Climate and Energy Policy
139 Framework, European Commission stated the target of achieving 15 % of existing electricity
140 interconnections for Member States which have not yet accomplished a minimum level of
141 integration in the EU energy market by the year 2030 [23]. Furthermore, importance of cooperation
142 between countries, governments, energy planners and utilities on both financial and policy side in

143 order to achieve economic growth when implementing RES is discussed in [24]. Abovementioned
144 papers present state of the art of energy system integration in SEE, with the focus on policies to
145 further integrate the region in the EU market.

146 Several papers deal with the planning of low-carbon energy systems with a high share of RES. In
147 [25] author describes approach in creating 100 % renewable energy systems that are technically
148 feasible, sustainable in terms of bioenergy use and economic competitive with fossil fuels.
149 Furthermore, authors in [26] presented a planning method of the 100 % independent Croatian
150 energy system with the special emphasis on RES, energy storage technologies and different
151 regulation strategies. In their work, they reached 78.4 % share of RES and significant CO₂
152 emissions reduction, concluding that in order to achieve 100 % independent or 100 % RES, a
153 detailed planning of all sectors has to be carried out. Similar research has been conducted in [27],
154 where 100 % renewable energy system for the case of Macedonia is presented as possible, but only
155 with a different storage technologies. However, in that scenario usage of biomass is too high taking
156 into account the national potential, so it was concluded that 50 % renewable energy system in the
157 year 2050 is much more realistic. Beside traditional uses of RES, there is a vast potential to exploit
158 new and emerging technologies such as high altitude wind energy [28]. High potential of
159 implementing this type of renewable energy in SEE region has been proved in [29]. Potential for
160 biogas production in one county of Croatia using a bottom-up methodology was assessed in [30].
161 Authors in [31] created three scenarios to reduce CO₂ emissions in Western Europe by 96 %, with
162 the shares of 40 %, 60 % and 80 % electricity production from RES. Transition of Mexican
163 electricity system from fossil fuels to RES has been presented in [32]. In order to meet the goals set
164 by the Mexican Congress, authors created three high-RES scenarios and achieved 35 % RES
165 electricity production in the year 2024, including sustainable use of biomass. However, they focus
166 only on the power generation sector and the latter does not include plans for the year 2050.

167 Furthermore, three scenarios for two countries in South East Asia for the year 2050 have been
168 created in [33]. Focus was on transition of electricity sector towards RES in order to reduce CO₂
169 emissions. As a result, they achieved the RES share of 40 % of total electricity production in
170 Indonesia and 39 % in Thailand. Novelty in this paper presents a 100 % renewable energy system
171 that includes integration of power, heat, gas and transport sectors in SEE.

172
173 Majority of the papers mentioned above focus solely on the integration of electricity markets in
174 SEE, excluding benefits from the cross-sector inter-regional integration. Exception is [34], where
175 100 % renewable SEE has been modelled. However, in their work too much emphasize was put on
176 power system, which led to unsustainable use of biomass. Consumption of 1,670 PJ of biomass was
177 calculated, while the sustainable potential is equal to only 730 PJ (Bulgaria, Greece and Romania
178 [35], Albania, B&H, Croatia, Macedonia, Montenegro and Serbia [36], Kosovo [37], Slovenia
179 [38]). Furthermore, excessive investment in pumped hydro storage (PHS) was assumed (increase of
180 15.6 GWh), which will be hard or almost impossible to meet taking into account PHS potential as
181 calculated in [39]. Improvement in the modelling approach in this paper compared to the [34] is the
182 sustainability in usage of biomass, which is met by a number of interactions between different
183 sectors of the energy system.

184
185 Thus, the novel approach shifts the focus from sectoral to a holistic view when modelling different
186 energy sectors, such as power, heat and gas systems (including mobility), augmented with the regional
187 integration of energy system (geographical integration). This approach leads to the detection of
188 synergies between different sectors and areas which would remain undetected by solely focusing on
189 partial solutions, such as smart grids, which allows more intermittent energy sources to be integrated in
190 the energy system. Furthermore, it makes transition to zero-carbon energy system feasible considering

191 only locally sustainable potential of the biomass, as opposed to studies where biomass import over the
192 system boundaries is allowed.

193

194 Another novelty is that the integration of 100% RES energy system is planned for regions that are
195 parts of the same synchronous electricity network and interconnected gas grids, but having different
196 political systems. Five of the analysed countries are EU member states, four candidate countries and
197 two potential candidates. The majority of them are members of European Network of Transmission
198 System Operators for Electricity ENTSO-E and the European Network of Transmission System
199 Operators for Gas ENTSO-G, while several countries act as observers in these associations.
200 Planning of 100% RES system in this way can show another benefit for mutual cooperation and
201 bonding on energy system planning.

202

203 Scenarios are developed for the reference year, which was set in this paper to 2012, and for the year
204 2050. The modelling tool used in this paper is EnergyPLAN. In the year 2050 the whole region is
205 considered to be 100 % renewable. In this paper the SEE region consists of eleven countries: Albania,
206 Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Kosovo, Macedonia, Montenegro, Romania,
207 Slovenia and Serbia.

208

209 The goal of this paper is to model a zero carbon energy system in a technically feasible way (critical
210 excess in electricity production needs to be less than 5 %, while the system is modelled as a closed one,
211 setting transmission capacity with the neighbouring countries to zero), using realistic measures and
212 penetrations of specific technologies, not exceeding their technical potentials. Furthermore, the system
213 needs to be robust and thus, it should not depend heavily on one technology; it should rather contain
214 mix of different technologies. Finally, the total socio-economic cost should be as low as possible,

215 keeping in mind that the system should be technically possible and realistic to achieve. Further novelty
216 in this paper is that the 100 % renewable SEE will be modelled by consuming biomass in a sustainable
217 way, i.e. within the limits of biomass potential in the region.

218

219 The second chapter of the paper is dedicated to the description of the methodology and EnergyPLAN
220 model, after which the case study and scenarios have been described in chapter 3. Results of the case
221 study are presented in chapter 4, while the discussion part focuses on the comparison of the results with
222 the other state of the art work. Finally, sensitivity analysis is carried out for the case of extremely dry
223 year, in order to assess the consequences of reduced hydro power plants production and possible water
224 scarcity due to climate change, followed by the main conclusions.

225

226 **2. METHODOLOGY**

227

228 In this paper, the concept of smart energy systems is adopted. Contrary to the concept of smart grids,
229 where emphasis is put only on one part of the energy system, the power sector, the concept of smart
230 energy system detects and utilizes synergies between different sectors of energy system, i.e. power
231 system, heating sector and gas grid [40]. Moreover, in order to adopt smart energy system concept
232 correctly, biomass has to be used in a sustainable way and thus, only certain part of forest residue
233 should be used as a primary energy source. A model, specially developed for modelling of smart
234 energy systems is EnergyPLAN, developed at Aalborg University [40].

235 Today, many different models for energy planning exist. A great review of energy planning tools is
236 given in [41]. According to it, out of many tools only seven of them incorporate electricity, heat and
237 transport sectors, while only four of them have already simulated 100 % renewable energy system,
238 i.e. EnergyPLAN, MesapPlaNet, INFORSE and LEAP. In this study, hourly analysis is preferred as

239 it allows detecting instabilities in the power grid, as well as the nature of critical excess in electricity
240 production, its frequency and the magnitude. Out of mentioned four modelling tools, only
241 EnergyPLAN and MesapPlaNet have the possibility of hourly time steps simulation. Furthermore,
242 MesapPlaNet has a very small number of users [41] and it was used only in Greenpeace studies for
243 simulation of 100 % renewable energy system in the year 2007 [42], 2008 [43], 2010 [44] and 2012
244 [45]. On the other hand, EnergyPLAN is already a well-established tool for modelling 100%
245 renewable energy systems. It was used for modelling of 100 % RES in the following countries:
246 Portugal [46], Macedonia [27], the Netherlands [47], Latvia [48], Ireland [49], Croatia [26] and
247 Denmark [50]. Overview of several 100 % renewable energy systems modelled was given in [51].
248 Furthermore, the model was used for the assessment of the 100 % renewable EU28 [52]. As it
249 satisfies all the needs for this study, EnergyPLAN was chosen to be a modelling tool for calculating
250 100 % renewable SEE in the year 2050.

251 The EnergyPLAN model is a detailed input/output model. Inputs that need to be set are energy
252 demands in general, renewable energy sources, energy conversion units such as electrolyzers,
253 energy plant capacities, costs and a regulation strategy. Outputs are energy balances and resulting
254 annual productions, fuel consumption, import/export and total costs including income from the
255 export of electricity [53].

256 Concerning the total system cost as an output of the model, it can present a socio-economic costs or
257 business economic costs. The socio-economic costs were used as an output in this paper, which
258 encompasses levelized investment costs of the energy plants over their lifetimes, fuel costs, fixed
259 and variable operating and maintenance costs, as well as CO₂ taxes as environmental externality. It
260 is worth mentioning here that taxes in general are not included in the calculation of socio-economic
261 costs as they are considered to be only internal redistributions within the society. Furthermore, costs
262 of implementing energy efficiency measures or advising costs of consulting companies during the

263 preparation phase of the projects are not incorporated in the socio-economic cost in this paper.
264 However, although implementing energy efficiency measures can impose high upfront costs, they
265 will be offset by the savings in energy spending. Hence, in the long term these measures will
266 actually lower the total socio-economic costs even more than calculated here.

267 Detection of health consequences and job creation opportunities are externalities that remained
268 outside of the scope of this paper when determining total socio-economic costs, although inclusion
269 of these figures would gain more beneficial results for renewables dominated energy system. In
270 support of the latter statement, authors in [54] calculated that the transition towards renewable
271 energy system in China in the year 2050 would create 4.12 million jobs. Furthermore, including
272 currently externalized health costs of the Danish heat and power sectors would decrease total health
273 costs by 18% [55]. It has been showed on the case of Taiwan in [56] that the net benefits of avoided
274 premature deaths, averted morbidity, savings in social costs and years of life lost are equal to
275 118,279 million USD during the period 2010-2030.

276 The model simulates energy system behaviour during one year in hourly resolution (8,784 steps)
277 and thus, it is a suitable tool for analysis of intermittent RES, as well as the hourly, daily and
278 seasonal fluctuations in energy demand.

279 The model can be applied from the municipality levels to the European level. The model describes
280 the interaction between the combined heat and power (CHP) plants and the RES especially well, in
281 the same time allowing the interplay between the heating and power systems. By various means
282 interplay between gas grids and the heating and electricity systems is well modelled, too [53].

283 On the other side, constraints of the model are its aggregated approach to power plants' modelling,
284 where all the thermal power plants are represented by the total capacity and fuel distribution
285 percentages between coal, natural gas, oil and biomass. Similarly, heat storages and district heating

plants are modelled only in three groups, which can possibly cause misinterpretation of the modelled system due to the geographical constraints that can occur in the real system. Furthermore, the system is treated as a single point without internal congestion management modelling. As a consequence, it cannot be clear from it whether there are disbalances and congestion in transmission and distribution networks between different regions and/or countries. Also, it is important to emphasize that the model does not distinguish between different types of biomass. An important comparison between optimization model such as TIMES and simulation model such as EnergyPLAN has been presented in [57].

The complete system interactions of the model can be seen in Figure 1:

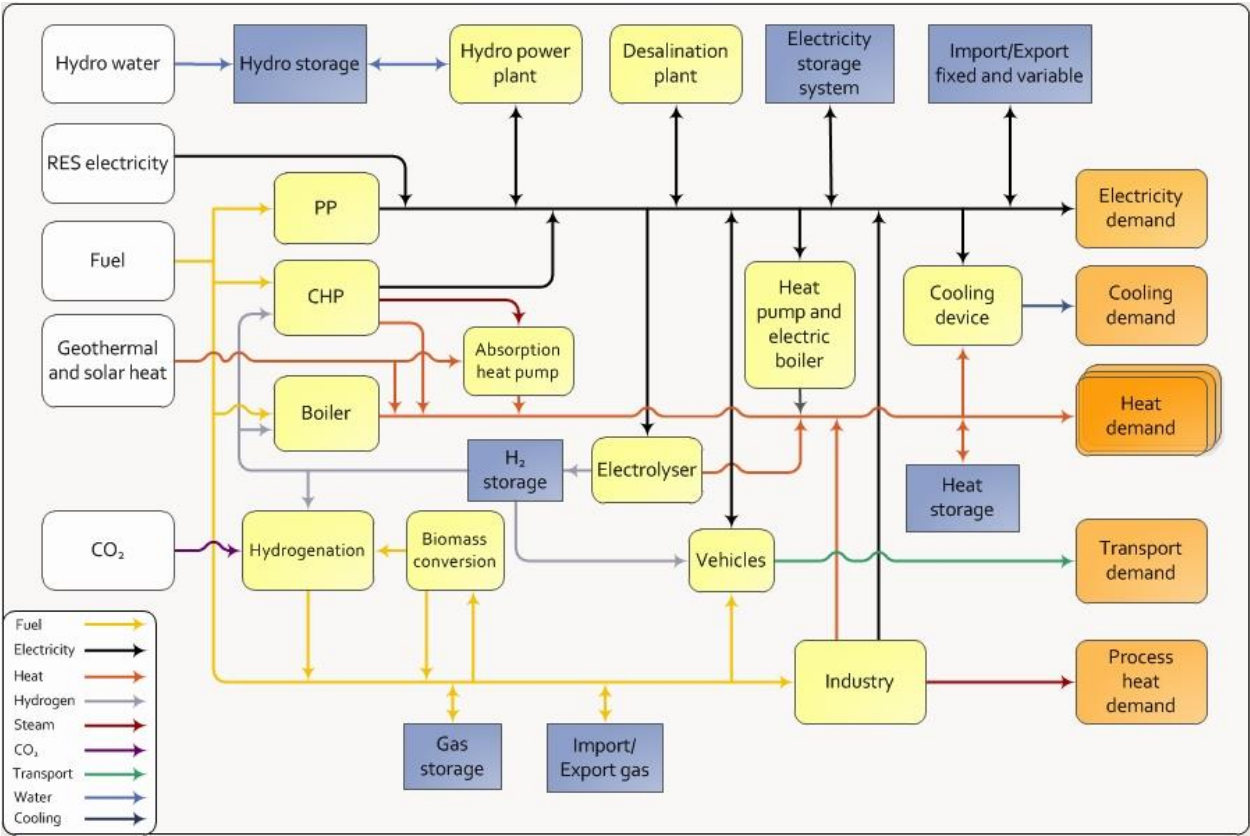


Figure 1. The EnergyPLAN model in version 11.4 [40]

298 Technical simulation will be used in the model, which seeks to find the solution with the minimum
299 consumption of fuels, i.e. with minimum emissions of CO₂.

300

301 **3. CASE STUDY: ZERO CARBON SEE IN THE YEAR 2050**

302 **3.1. Reference energy system (2012)**

303

304 Reference energy system was built for every country independently, validated against the International
305 Energy Agency's data [58] and then joined together in the one energy system.

306 Electricity data was obtained from ENTSO-E [59], except for Albania and Kosovo, countries for which
307 the electricity data is not available on ENTSO-E. Demand for these countries was calculated by
308 obtaining monthly demand values from [50] and [51] and scaling it on hourly resolution using the
309 average of other SEE countries' profiles. As these two countries represent only 7 % of the total
310 population in SEE, this assumption will not cause a significant impact on overall results. Heat demand
311 was calculated using the degree-hour method, while the hourly temperatures were obtained from [62].
312 Solar radiation curves, river hydro and dammed hydro distribution profiles were used for the year 2008
313 [40] and adapted to the yearly values of hydroelectric power plants generation obtained from the
314 International Energy Agency (IEA) [58].

315 Wind speed data was obtained from EnergyPLAN database of measured data for the year 2008 [25]
316 and adapted to the capacity factor in 2050 as calculated in [63]. As showed in [45] and [46], average
317 yearly wind speed is usually between the 10 % range from the mean and seldom in the range of 20 %
318 from the mean for the specific location. Furthermore, as the system modelled is not excessively
319 dependent on wind (less than one third of the electricity generation), it is assumed that the system is

320 robust enough to deal with these small fluctuations between different years. Moreover, as the modelled
321 geographic area is large, the differences in annual wind speeds for a specific location flattens out when
322 many wind farm locations are considered.

323 Economic data, which includes investment costs, energy plant lifetimes, fixed and variable operating
324 and maintenance costs were taken from the official website of the model developers [40]. The cost
325 database is constantly being updated and can be freely accessed. Discount rate was set to 3% and CO2
326 emissions cost in the year 2050 is set to 46 €/ton. However, the latter number does not have any
327 influence upon the result as the system in 2050 is already the zero-carbon one.

328 The majority of capacity in SEE is linked with thermal and hydroelectric power plants, i.e. 37.8 and
329 23.1 GW. Out of total capacity of hydroelectric power plants, 83.6 % are dammed power plants
330 (including cascade power plants), while 16.4 % are run-of-river hydro power plants. Nuclear power
331 plants are installed in Romania, Bulgaria and Slovenia with the total capacity of nearly 4 GW. Wind
332 energy is a dominant RES technology with installed capacity of 4.6 GW in 2012, followed by
333 photovoltaics (PVs) with installed capacity of 2.2 GW.

334 A detailed list of power plants for each country for the year 2012 can be seen in Table 1.

335 **Table 1. Installed generation capacity in the SEE Region**

Country	Year	Ref.	Hydro [MW]	Thermal [MW]	Nuclear [MW]	Biomass [MW]	Wind [MW]	PV [MW]	Other RES [MW]
Albania	2012	[66]	1,450	0	0	0	0	0	0

B&H	2012	[67]	2,034	1,590	0	0	0	2.4 [68]	0
Bulgaria	2012	[69]	2,864	6,613	2,000	20 [70]	684	908	0
Croatia	2012	[71]	2,136	1,681	0	13.8	180	4	0
Greece	2012	[69]	2,817	9,741	0	39	1,865	1,039	0
Macedonia	2012	[72]	578	800	0	0	0	1.6	0
Montenegro	2012	[73]	660	208	0	0	0	0	0
Romania	2012	[74]	6,195	9,460 [75]	1,300	89	1,905	51	0
Serbia	2012	[76]	2,910	4,642	0	0	0	0	0

Slovenia	2012	[77]	1,254	1,495	6,96	41	2	240	0
Kosovo	2012	[78]	43	885	0	0	0	0	0
TOTAL	2012		22,941	37,115	3,996	202.8	4,636	2,246	0

336

337 The CO₂ contents of 74 kg/GJ for fuel oil, diesel and petrol, 56.7 kg/GJ for natural gas and 101.2
338 kg/GJ for coal have been used in the analyses [40].

339 **3.2. Zero Carbon Energy System in 2050**

340

341 Building a 100 % renewable energy system, while consuming biomass in a sustainable way consists of
342 several steps.

343 Firstly, power and district heating sectors need to be integrated in order to allow more than 20 % of
344 intermittent electricity production (wind and PVs). The integration of these two sectors needs to be
345 achieved by advanced CHPs and heat pumps coupled with thermal energy storage, in order to increase
346 efficiency of the system and reduce the overall fuel consumption. Secondly, electrification of majority
347 of light vehicles needs to be introduced. Vehicle-to-grid (V2G) technology needs to be implemented in
348 order to help balancing out the electrical grid. Moreover, where possible, pumped storage hydroelectric
349 power plants need to be installed to further improve integration of intermittent energy sources. A next
350 step is penetration of wind power and PVs on a large scale, especially as for the latter technology a

351 significant drop in investment costs is anticipated. Furthermore, other RES such as waste incineration
 352 power plants, small hydro power plants and concentrated solar power with thermal storage (CSP) are
 353 introduced. In the heating sector, it is especially important to introduce geothermal energy on a large
 354 scale.

355 In the transportation sector, medium and heavyweight vehicles which cannot be electrified by current
 356 battery technology need to be fuelled by either biofuels or electrofuels. As technologies for electrofuels
 357 are still not in the commercial phase, majority of transportation means is assumed to be driven by
 358 biofuels or synthetic fuels produced from biomass.

359 In individual heating sector, parts of houses and buildings which cannot be connected to district
 360 heating grid need to be heated by heat pumps or solar thermal energy. If none of these technologies are
 361 suitable, individual biomass boiler technology will still be used.

362 Overview of measures on the demand side of the model and references of each implemented measure
 363 can be seen in the Table 2. On the other hand, measures implemented on the supply side of the system
 364 are presented in the Table 3.

365 In order to reach the 100 % renewable energy system in the year 2050, following steps were made:

366 **Table 2. Measures on the demand side of the system**

Measure	Ref	Discussion
Efficiency increase in individual houses by 50 %	[79]	In Energy Efficiency scenario of Energy Roadmap 2050 a staggering 72 % of increased efficiency is assumed; it is assumed here that it is exaggerated, as it was argued in [52] and thus, 50 % of increased efficiency is assumed
Energy efficiency increase of 50 % in households supplied by district heating	[79]	In Energy Efficiency scenario of Energy Roadmap 2050 a staggering 72 % of increased efficiency is assumed; it is assumed here that it is

		exaggerated, as it was argued in [52] and thus, 50 % of increased efficiency is assumed
Replacement of 52.5 % of individual heating houses with small scale district heating (1.5 % per year)	[52]	In Heat Roadmap Europe 2050 an increase in DH from 12 % to 50 % is assumed for the same period. As the penetration in the base year for SEE is already higher than 20 %, it is assumed that it is viable to achieve the penetration of DH of 51.5 %. Furthermore, in [80] it was shown that small scale biomass driven cogeneration system is economic feasible investment if pit thermal energy storage is used for peak purposes instead of boilers
50 % of final heating demand of houses not connected to the DH is met by heat pumps, 20 % by solar thermal and 30 % by biomass boilers	[81]	Measures adopted from the references with slightly higher share of biomass adopted as it is expected due to the much larger penetration of biomass nowadays that a slightly larger share will it have in the year 2050.
In industry, increased efficiency of 2 % per year is leveled out with the same increase in industrial activity, which is set to 2 % per year in average for the whole region	[52]	Measure adopted from the reference without any modifications. There are many measures for increase of energy efficiency in industry, e.g. [82] showed the possibility of achieving energy savings of 8.2 % in a crude distillation unit using the process integration techniques.
20 % of demand in industry is met by industrial CHPs	[52]	Measure adopted from the reference without any modifications.
15 % of demand is met by solar thermal energy with storages	[83]	According to the reference share of solar thermal energy in industry could reach up to 33 %. More conservative approach was assumed in this paper and a share of 15 % has been adopted
45 % of energy demand of fossil fuels in industry is replaced with electricity	[84]	New efficient induction furnaces are coming to the market. As shown in the reference, induction plant can replace conventional gas or oil-fired furnace, significantly reducing the consumption of fuels and as a consequence lower the greenhouse gas emissions (GHG). Thus, it is assumed that a large portion of energy intensive industries will shift to

		induction furnaces.
Remaining coal and oil consumption is replaced by biomass	[81]	Measure adopted from the reference without any alterations.
In transport sector 20 % energy savings needs to be achieved by improved public transportation system and replacement of one part of individual vehicles with public transportation (mainly electrified trains)	[81]	Measure adopted from the reference without any alterations.
Total electrification of railway system	[81]	Measure adopted from the reference without any alterations.
100 % of light transport vehicles and 35 % of medium transport vehicles is replaced by electrical vehicles; out of these 85 % will be using smart charge system, while 15 % dumb charge system	[81]	Measure adopted from the reference without any alterations.
Remaining part of transport sector demand is met by synthetic fuels produced mainly by chemical synthesis from biogas (hydrogenation of biomass); 25 % of fuel demand is met by CO ₂ hydrogenation using electricity as energy input	[85]	As using biomass (e.g. rapeseed) for biofuels has been criticized due to the competition with the food supply chain, land use impacts [86], sustainability problem and impacts on land resources [87],a hydrogenation of biomass was introduced as it uses less biomass from biofuels and better integrates intermittent RES in the system [85].

367

368 On the supply side following steps are made:

369 **Table 3. Measures on the supply side of the energy system**

Measure	Ref	Discussion
Total capacity of wind set to 50 GW	[63,88]	According to the references, the total economic viable wind potential is 137 GW. However, more conservative approach has been adopted. (Greece, Romania and Bulgaria [88], other SEE countries from [63])
Total capacity of PVs set to 65 GW	[63]	According to the reference, up to 50 % of final electricity demand could come from PVs in this region.
Total capacity of CSP set to 11 GW	[89]	According to the reference Spain installed 1.3 GW of CSP from 2006-2012. Thus, 11 GW of CSP in the SEE till the year 2050 was assumed as a viable estimate. (2020-2030 2.5 GW, 2030-2040 3.5 GW and period 2040-2050 5 GW of installed capacity)
Increase in dammed hydro power capacity for 25 %, to 23.5 GW	[90]	According to the reference, technical and economic feasible potential in this region is still huge and hydropower could be increased by more than two times. However, due to complicated procedure when building dammed hydro much more conservative approach has been adopted
Introduction of 1.5 GW _e of large scale heat pumps	[91–93]	As it was shown in the references, large scale heat pumps are beneficial technology (to solve intermittency and efficiency problems [91], beneficial in cooperation with CHP systems [92] and beneficial in implementing high share of RES [93]) for integration of intermittent RES and thus, this technology has been introduced.
13.3 % of heat in DH system is met by solar thermal with a 75 GWh of seasonal thermal energy storage	[94]	According to the reference, in municipality of Sønderborg in Denmark a 20 % of DH demand is projected to be supplied by solar thermal. Due to the much larger systems and higher winter peaks, a smaller share of solar thermal has been assumed to stay on the safe side
All newly introduced district heating goes to the small scale networks	[80]	It was shown in the reference that small scale DH networks are economic feasible in current support system, as well in Feed-in premium system

Installation of 230 GWh of seasonal storage in DH network	[95][96]	In Zagreb, a seasonal storage of 750 MWh has been built already [95]. However, due to the large return temperature losses are higher than usual and the real capacity of this storage in optimal regime is 1.5 GWh. In ref [96] it was shown that in Denmark already today a three times larger storages exist. Thus, it is assumed that each country will build four storages with equivalent size of the storage built in Marstal, Denmark with the capacity of 5 GWh
960 MWe and 2.38 GWh of waste incineration power plants	[52][97]	Calculated from Heat Roadmap Europe and scaled due to the population ratio of SEE and EU28 [52]. It is assumed that similar amount of waste is produced per person. However, to be on the safe side the total potential has been reduced by 20 %. Technical data for waste incineration plant was obtained from Energinet's report [97].
1,250 MWe of geothermal PP	[98–100]	Technical potential (Croatia and Greece [98], Bulgaria and Romania [100], Albania, B&H, Kosovo, Macedonia, Montenegro, Serbia and Slovenia [99]) adopted without any alterations.
Adding 7.5 GW of geothermal heating energy (in 2050 40 % of heat in DH is produced by geothermal energy sources)	[98–100]	Technical potential (Croatia and Greece [98], Bulgaria and Romania [100], Albania, B&H, Kosovo, Macedonia, Montenegro, Serbia and Slovenia [99]) adopted without any alterations.
Increase in river hydro and small hydropower plants to 6.8 GW	[90,101]	According to [90], SEE utilizes only 41% of economic hydro potential. Furthermore, [101] estimates much higher potential for each individual country. However, conservative approach has been adapted to be on the safe side.
Increase in CHP capacity to 8 GW	[52]	Adopted according to the reference.
Reduction in thermal power plants capacity to 24.7 GW	[50]	Adopted according to the reference. The capacity of thermal power plants, as stated in Table 1, is assumed to be gradually reduced towards

and replacing its fuel with biomass		24.7 GW, decommissioning the old thermal power plants upon the end of their lifetimes.
Decommission of all nuclear power plants		Due to inflexible operation , high capital costs and already long operation time it is also not envisaged to have new installations after 2025
Introduction of 11 power plants similar to Avča (total new storage 1,067 GWh (obtained from [39], pumping capacity 1,980 MW and turbine capacity 2,035 MW)	[39]	Storage within 5 km distance from the lower lake has been taken from the reference as a viable potential

4. RESULTS

Analyses were made in EnergyPLAN looking at SEE as a closed system and thus, transmission capacity to neighbouring countries was set to zero. Thus, all the generated excess electricity was considered to be a critical one and abbreviation CEEP is used to denote it (Critical Excess in Electricity Production).

4.1. Reference scenario validation

In order to validate the model, reference scenario made for the year 2012 was validated against the data obtained from the IEA [58].

381 **Table 4. Validation of reference model**

	IEA	EnergyPLAN	Difference
	SEE	SEE (TWh)	IEA -
	(TWh)		EnergyPLAN
Coal	466.4	468.3	-0.40 %
Oil	438.3	437.8	0.12 %
Ngas	256.5	256.9	-0.15 %
Nuclear	99.6	99.5	0.15 %
Hydro	49.1	49.7	-1.26 %
Biomass	113.2	113.8	-0.55 %
Other	23.0	0.0	
CO2	320.7	332.0	-3.52 %
(Mt)			
PES	1,446.2	1,426.0	1.39 %

382

383 As it can be seen from Table 4, the reference model developed for the year 2012 matches well with the
384 data obtained from the IEA. The total CO₂ emissions differ 3.5 %, while total primary energy supply
385 differs for 1.4 %. It can be also seen that resulting fuel emissions are slightly different in the reference
386 model compared to the IEA data, as the difference in CO₂ emissions is slightly greater than the primary
387 energy supply (PES) difference.

388 **4.2. Comparison of energy systems in years 2012 and 2050**

389

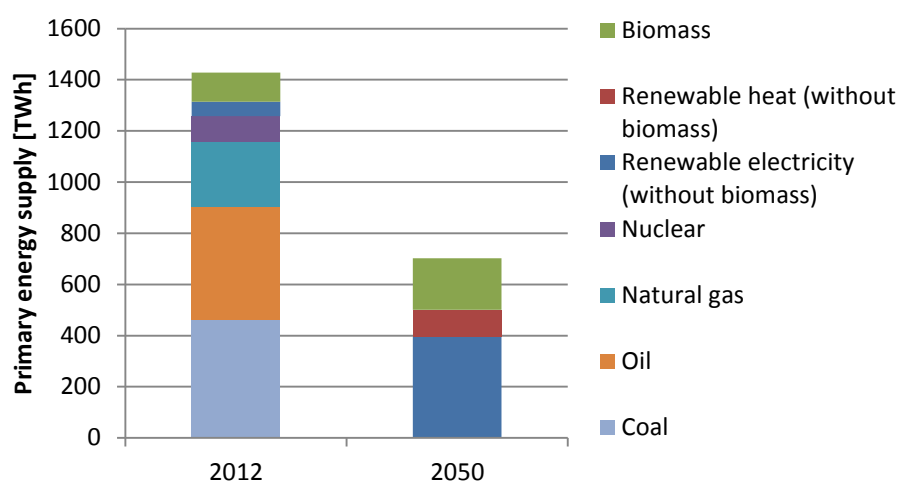


Figure 2. Primary energy supply in the year 2012 and 2050

In Figure 2 the total primary energy supply for the year 2012 and 2050 can be seen. In 2050, the whole energy supply is renewable and the total biomass consumption is sustainable, i.e. its consumption is equal to 201.65 TWh. Biomass potential in all countries for the year 2012 can be seen in Table 5.

Table 5. Biomass potential of countries located in SEE (Bulgaria, Greece and Romania [35], Albania, B&H, Croatia, Macedonia, Montenegro and Serbia [36], Kosovo [37] and Slovenia [38])

Biomass potential	PJ	TWh
Slovenia	19.6	5.4
Greece	27.10	7.5
Croatia	56.14	15.6
Montenegro	12.03	3.3
Serbia	136.8	38.0

B&H	56.41	15.7
Albania	29.79	8.3
Kosovo	4.85	1.3
Macedonia	21.61	6.0
Bulgaria	44.36	12.3
Romania	318.03	88.3
Total:	726.74	201.9

399

400 Thus, modelled biomass consumption is within the biomass potential. According to the reference
401 [102], 71% of the total potential of sustainable biomass in Western Balkans (Albania, B&H,
402 Croatia, Macedonia, Kosovo, Montenegro and Serbia is attributed to woody biomass (i.e. residuals
403 from wood industry, logging residuals, residuals from pruning different fruit trees, olive trees or
404 vineyards and firewood) and 29% to agricultural biomass (i.e. food-based and nonfood-based
405 portions of crops such as wheat, barley or corn residuals). Therefore, the same share can be used for
406 the SEE region in this case.

407 In Figure 3, detailed renewable energy generation by sources can be observed.

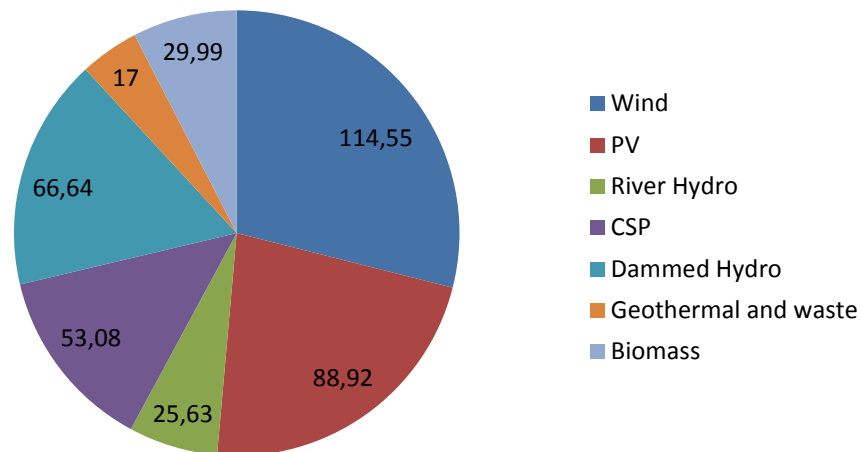
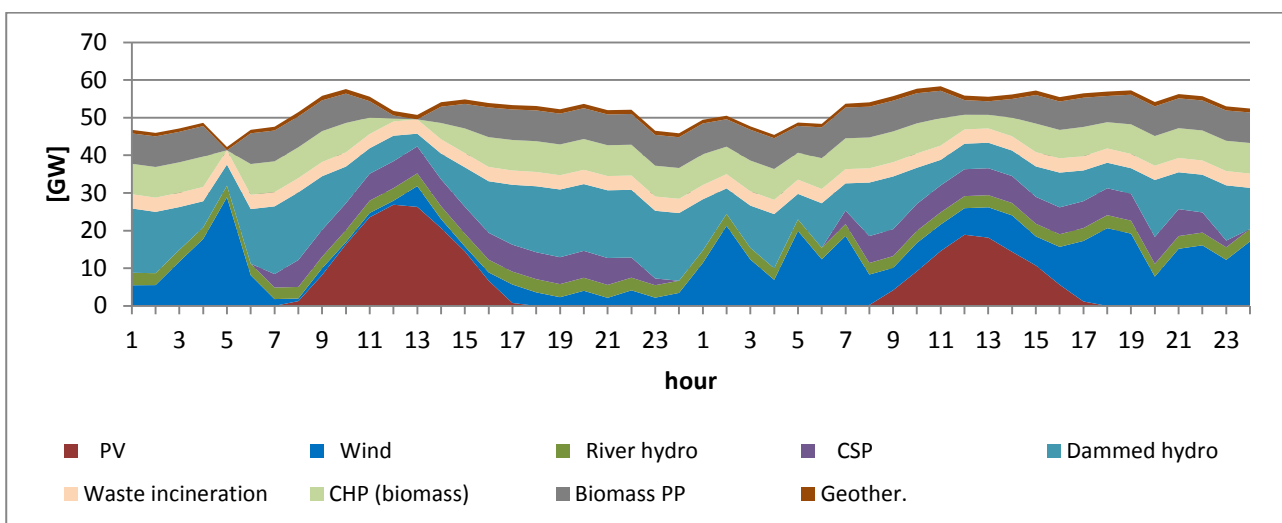
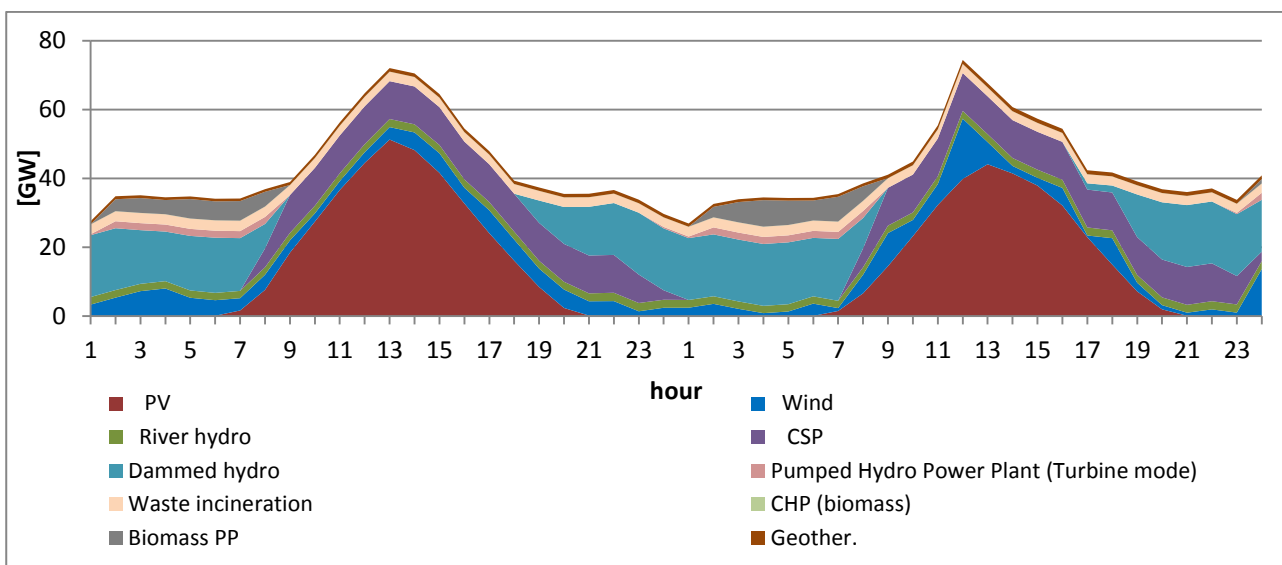


Figure 3. Mix of renewable electricity generation in the year 2050 [TWh]

The largest share in electricity production have wind and PVs with 28.9 % and 22.5 %, followed by dammed hydro, CSP, biomass driven plants (mainly CHPs), geothermal and river hydro. It is important to note that none of technologies exceed 30 % of generation share on yearly basis, which shows that the system is robust and is able to cope with fluctuations in generation of specific technologies between the different years. Moreover, large geographic scale of integrated energy system of SEE evens out fluctuations of certain generation technologies at a local level.

It is interesting to compare generation of electricity on hourly resolution during the two days in summer and winter, which is presented in Figure 4:



421 **Figure 4. Electricity generation mix during two days in mid-July (up) and in the beginning of**
 422 **January**

423

424 It can be seen that PVs are dominating the generation mix during the summer. Beneficial feature of the
 425 power system during the summer is that PV production corresponds to the peak consumption. In the
 426 summer day during the evening and night, the majority of generation comes from dammed hydro
 427 plants. Furthermore, it should be noted that the pump hydro plants are working during the night with

the maximum capacity in the turbine regime, which adds 2 GW of power generation capacity, helping to meet the overall electricity demand as the night in the mid-July being presented had very low wind production.

During the winter, generation of PVs is on a much lower scale. Dammed hydro production had a large share of generation during the evening. However, during the night in winter period, dammed hydro production is lowered down due to the higher generation of wind energy. Moreover, the peak demand and the trough demand do not differ as much as during the summer period.

Finally, evaluation of the energy system from the technical point of view in the year 2050, compared to the current system (2012), can be assessed by taking a closer look at the data presented in Table 6.

Table 6. Comparison of different parameters of energy systems in the year 2012 and 2050

	2012	2050
PES [TWh]	1,426	702.86
CO2 emissions [Mt]	332	0
CEEP [TWh]	0	15.64
Total annual socio-economic cost [MEUR]	63,903	44,415

It can be seen from Table 6 that the primary energy supply has decreased significantly (50.7 %), while the CO₂ emissions reduced to zero in the year 2050. Critical excess in electricity production is equal to 15.64 TWh or 4.4 % of the total electricity production. However, it is important to note here once again that the system of the SEE was modelled as a closed system, without transmission to the neighbouring countries. By using different strategies, such as gasification and production of synthetic fuels when there is an excess in electricity production, CEEP can easily be reduced for 50 %. Nevertheless, further

decrease in CEEP can be achieved by introducing the transmission capacity to the neighbouring countries [103]. It is worth mentioning here that besides having 100 % renewable energy system in the year 2050, the total annual socio-economic cost is almost 20 billion EUR lower in the year 2050 compared to the reference year. Thus, although higher costs can occur during the initial phases of transformation to the 100 % renewable energy system due to the high upfront costs, the final energy system can be cheaper compared to the one heavily dependent on fossil fuels.

5. DISCUSSION

In [80] authors presented biomass driven trigeneration system coupled with pit thermal energy storage on a case study for one district in Croatia. They have showed that building small scale cogeneration units can be beneficial in economic terms. This approach has been also confirmed in this model, as small scale CHP systems increase fuel efficiency of the system and thus, decrease the total biomass consumption. Furthermore, along with the heat pumps and thermal storage, CHP plants are used to integrate heating and power sectors which leads to further increase in efficiency.

In [104] the influence of energy policy on energy demand was assessed on a case study of Croatia. By inclusion of policy measures in different scenarios, achieved energy efficiency improvements equalled to 23 % in industry, 25 % in households and 27 % in transportation sector. Total savings in PES after the measures were adopted equalled 22 %. Moreover, overall biomass consumption for the case of Croatia is not completely clear so the sustainability in usage of biomass remained unclear.

In this paper, measures proposed in several different papers for the case of Denmark, Energy roadmap 2050 and Heat roadmap 2050 were adapted or directly adopted. Moreover, certain energy efficiency goals proposed in Energy roadmap 2050 were argued as exaggerated and measures from other

467 references were adopted. By using referenced energy efficiency measures in this paper, a total primary
468 energy savings equalled to a significant 50.7 %. Although the expenses for increased energy efficiency
469 measures are greater in the beginning, the total socio-economic costs for the year 2050 will be lower.

470 In [63], the biomass consumption was unsustainable, as already shown in the introduction, and the
471 excessive investment in pumped hydro storage was assumed. Furthermore, primary energy supply is
472 equal to 943.6 TWh and the largest share in electricity consumption has wind (34 %), followed by PV
473 (20 %), river hydro (14.4 %) and pumped hydro plant (14 %) generation. Yearly modelled biomass
474 consumption amounts to 1,690 PJ. Reported CO₂ emissions in 2050 are equal to zero while primary
475 energy supply is 33.8 % lower compared to the reference year (2008).

476 In this paper total primary energy savings are equal to 50.7 %, 726 PJ of biomass is consumed annually
477 and pumped hydro storage is increased only till its technical limit as referenced in Table 3. Thus, PES
478 in this paper is 34 % lower and the biomass consumption is 57 % lower than in [63]. This proves that
479 greater energy efficiency of the system can be achieved by the better integration of the whole energy
480 system, compared to the solely focusing on the power sector. Furthermore, biomass consumption in
481 integrated energy system can be reduced to the sustainable level.

482 It is of crucial importance to clarify that the statement “*the better integration of the whole energy*
483 *system*” refers to the integration of power, heating and gas sectors (including transportation),
484 complemented with the regional integration (geographical integration) of the energy systems. This
485 integration leads to the better technical system in terms of managing the intermittent energy sources
486 and robustness of the modelled system in general, as well as to cheaper energy system considering the
487 socio-economic costs. On the other hand, taking only power sector into consideration, in so called
488 smart grids, leads to the partial solution that cannot detect possible synergies between different energy
489 sectors. As a consequence, the latter approach will lead to either more expensive system in terms of

490 socio-economic costs or to less viable energy system from technical point of view, represented in the
491 ability to integrate intermittent renewable energy sources.

492 The possibility of carbon capture and storage (CCS), coupled with coal fired thermal power plant in the
493 SEE has been assessed in [105]. The ultra-supercritical pulverized coal power plant with and without
494 CCS was assessed. Authors have used levelized cost of electricity (LCOE) assessment for showing the
495 viability of investment in the power plant. In the case without the CCS, the calculated LCOE was
496 57.25 €/MWh, while in the case with installed CCS the LCOE was 92.42 €/MWh. Assumed carbon
497 price was 10 €/tCO₂, while the assumed running times of the power plant were 7,200 h and 7,600 h. In
498 the sensitivity analysis authors have shown that reduction in availability of 10 % can increase the
499 LCOE cost for up to 6 €/MWh. It would be even more interesting to see the calculated LCOE with the
500 running time of around 5,000 hours (35 % reduction in availability), as it can be assumed that the
501 LCOE result would be even worse.

502 The latter finding is crucial here. The electricity price is formed on market according to the supply and
503 demand. Supply curve is built according to merit order of every power plant. Power plants bid their
504 offers according to variable costs of electricity generation and in the case of PVs, wind energy, run-of-
505 river hydro and CSP this cost is zero. Thus, power plant which uses fuel, such as coal, needs to make
506 its offer at some higher price as it least needs to cover the costs of fuel and other variable costs. When
507 there is a lot of electricity production from wind or solar energy, the marginal cost of electricity will be
508 very low, much lower than the cost of electricity generation from coal power plant. This leads to the
509 conclusion that there will be many hours when electricity generation is dominated by wind and solar
510 sources (as shown in Fig.3 and 4), forcing the coal fired power plants to be shut down in these hours.
511 As a result, coal fired power plants will have much lower number of running hours throughout the year
512 than assumed in [105], which results in economic unfavourable indicators. Although in some countries
513 of SEE the El-spot market still has not been set in place, it is expected that this will happen in the near

514 future and thus, investment in coal power plants, both with or without CCS, will be economic unviable.
515 Because of this reasoning, new coal fired power plant investments should not be considered when
516 planning the future energy system development.

517 Authors in [106] presented the methodology developed in the RE-SEETies: “Towards resource
518 efficient urban communities in SEE” project, focusing on overview of urban energy and waste
519 management systems of communities in SEE. They suggested integrated, transnational approach to
520 promote RES and energy efficiency measures. The project resulted in many recommendations for
521 successful implementation of energy efficiency measures, increase of public acceptance for RES and
522 waste handling (both recycling and waste-to-energy).

523 Many recommendations and findings in the mentioned paper coincide with the measures proposed in
524 this paper. Some of these measures are: increase in energy efficiency, waste-to-energy utilization, RES
525 penetration, choosing ambitious goals, transnational (regional) cooperation and integrated approach in
526 transformation of energy system towards a low-carbon one. It can be concluded that both papers strive
527 towards the sustainable society and are mutually complementing. This paper deals more with the
528 technical side of the problem and the pathway towards reaching the 100 % renewable energy system,
529 while [106] puts more emphasize on the implementation of specific measures and recommendations
530 for cooperation between different stakeholders.

531 Thus, compared to the previous papers with case studies being done in the region of SEE, it is shown
532 in this paper that integrated and holistic approach to the whole energy system can open the space for
533 the detection of additional benefits for the system which can improve the system from technical point
534 of view. Furthermore, a holistic approach when adopting certain energy efficiency measures or
535 measures on promotion of certain technologies on the supply side of the energy system can reduce the
536 total annual socio-economic costs of the energy system.

Technical calculations are just the stepping stone but joint energy planning can have more benefits as in the case of electricity and gas transmissions system planning. To have a common policy, such as achieving zero carbon systems for SEE, can have benefits in terms of security of investments, economies of scale, joint public private partnerships and technology development, especially towards sustainable energy technologies such as ecologically harmless hydropower plants. All these benefits need to be further elaborated and addressed in the further research.

6. SENSITIVITY ANALYSIS

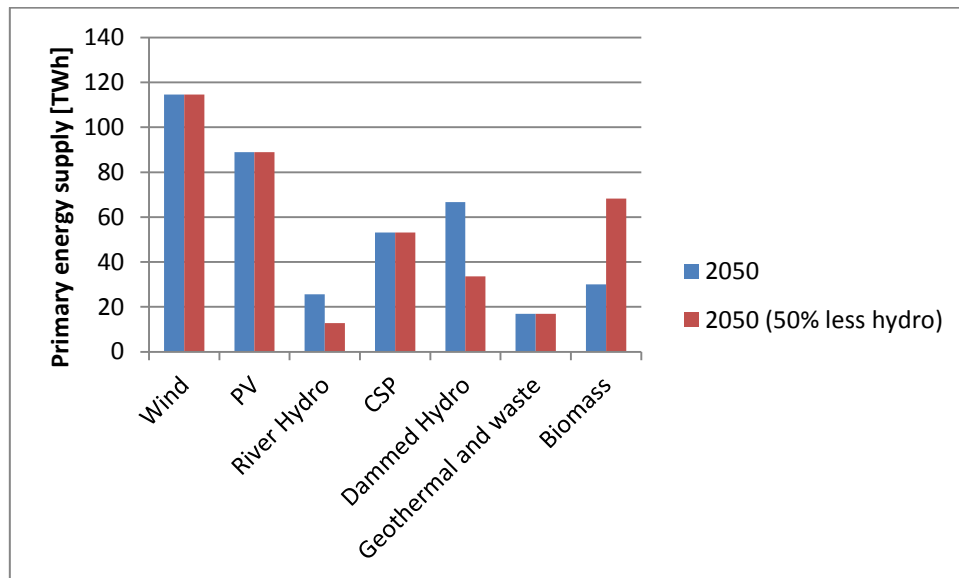
As shown in [71] for the case of Croatia, hydro power plants production can deviate from the mean value for up to 47 %. Although in the last decade the highest extremes were showing during the wet years, the sensitivity analysis will be carried out assuming that the extreme will show up during the dry year. As similar conditions appear in all the countries of the region, a sensitivity analysis with 50 % less production of hydro power plants has been carried out.

Table 7. Comparison of results obtained in sensitivity analysis.

	2050	2050
50 % less hydro		
PES [TWh]	748.4	702.86
CO2 emissions [Mt]	0	0
CEEP [TWh]	13.85	15.64
Biomass	1,044	726
Consumption [PJ]		
Total annual socio-	47,900	44,415

551

552 As it can be seen from Table 7, during the extremely dry year biomass consumption can become
 553 unsustainable. Moreover, during the dry year additional space for renewable technology such as wind
 554 can occur. Increase in biomass consumption during the dry year equals to a significant 43.8 %. In
 555 Figure 5, it can be seen that there is no capacity in other renewable technologies and biomass driven
 556 plants need to take over all the missing hydro production.



557

558 **Figure 5. Difference in electricity generation during sensitivity analysis**

559

560 Thus, in order to achieve the sustainable use of biomass on projected extremely dry year, an additional
 561 capacity of renewable technologies should be installed. However, the projected dry year is a real
 562 extreme and the ‘savings’ in biomass during the wet year can cover the unsustainable use of biomass
 563 during the dry year. This reasoning stems from the research carried out for the case of Norway in
 564 which was shown that the wet years occur three times more frequently compared to dry year [40].

Moreover, long-term melt-down of glaciers in Austrian Alps can cause increased flow in downstream rivers, which can increase hydropower potential during the melting season from May to October as shown in [107]. However, ever increasing melting rate of snow can reduce its ability to serve as accumulation, which can cause floods and more intermittent production of hydro power plants. By this example it can be seen that climate modelling is crucial in planning of future energy systems.

7. CONCLUSION

In this paper, energy system of SEE has been analysed. It was clearly shown that 100 % renewable energy system of the whole region is possible by taking many steps in different sectors during the transformation phase to zero carbon society. Furthermore, to achieve 100 % renewable energy system, and in the same time sustainable in terms of biomass consumption, integration between different sectors of energy systems is needed in order to increase overall efficiency of the system. By integrating energy systems, carefully interacting within them and investing in heating energy storage, serious savings in primary energy consumption can be achieved. It is of great importance to maximally utilize cheap gas and heating energy storage (compared to electrical one), as well as electrical storage in vehicles, following V2G concept, in order to have the attractive system from economic point of view, too. Following these steps, a developed renewable energy system of the SEE consumed 702.86 TWh of primary energy, 50.7 % less compared to the year 2012. Furthermore, the system reached zero-carbon emissions in a technically viable way as the CEEP remained below the 5 %, i.e. it was 4.4 %. The modelled power system is robust as neither of generation technologies exceeds 30 % of the total generation mix. Among them, wind and PV are dominant technologies with the generation shares of 28.9 and 22.5 %, respectively. Installed thermal capacity is reduced from 37.1 to 24.7 GWs, its yearly load factor is 14.8% and they are completely driven by biomass. The load factor of these plants does

not need to be high as their use in the future system is only to cover the periods when there are no fuel-free generation options available. Finally, integrated regional energy system of the future has 30.5 % lower total yearly socio-economic costs compared to the current system.

In order to consume biomass in a sustainable way, some type of synthetic fuel is needed. In this paper, the chosen technology was hydrogenation of biomass, which increases the efficiency in the transportation sector and reduces biomass consumption compared to the usage of biofuels. For the case of the SEE the consumption of biomass (726 PJ) is just under its sustainable potential (726.74 PJ). This is an important improvement compared to the previous work in which 1,670 PJ of biomass consumption was assumed for the same region [34].

Sensitivity analysis showed that the system could face with unsustainable use of biomass on extremely dry year. However, this should be covered by ‘savings’ in biomass during the wet years. Nevertheless, this leads to the conclusion that an emphasis should be put on climate modelling in the future research.

Finally, although it is shown that it is possible, many serious steps, coordinated on a large scale, have to be made in order to gradually switch the SEE energy system from fossil dependent one to 100 % renewable one.

8. ACKNOWLEDGMENT

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